Development of a Gridless Retarding Potential Analyser

IEPC-2017-271

Presented at the 35th International Electric Propulsion Conference
Georgia Institute of Technology – Atlanta, Georgia – USA
October 8–12, 2017

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Abstract: Since 2009, Airbus in Friedrichshafen has been down-scaling the High Efficiency Multistage Plasma Thruster (HEMPT) principle to the micro-Newton regime to evaluate the capability of the HEMPT for LISA-like missions. In this context, a test environment has been built that is capable of analysing potential thruster candidates with 15 gridless retarding potential analysers (gRPA). In order to evaluate this novel approach for a RPA sensor concept a 3D numerical particle tracing has been conducted. The sensor has an acceptance angle of 5° and is in the current stage of development capable of applying an retarding potential of 1500 V. In order to assess thruster in different power classes, a variable gain has been implemented allowing measurements of beam current densities between 7.3 nA/cm² to 2.5 mA/cm².

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Nomenclature

COTS = Commercial-of-the-shelf
HEMPT = High Efficiency Multistage Plasma Thruster
HET = Hall-Effect Thruster
RIT = Radiofrequency Ion Thruster
$I_{sp}$ = Specific impulse
$PTTR$ = Power to thrust ratio
$T$ = Thrust
$\gamma$ = Divergence efficiency
$\theta$ = Divergence angle
$\eta_e$ = Electrical efficiency
$\eta_d$ = Discharge efficiency
$\eta_v$ = Acceleration efficiency
$\eta_m$ = Mass efficiency
$P_{in}$ = Thruster input power
I. Introduction

Plasma engines are a major class of electric propulsion thrusters. The concepts vary significantly between different ion drives as for example gridded ion engines have separated mechanisms for propellant ionization and ion acceleration whereas Hall-Effect thrusters (HET) or High Efficiency Multistage Plasma Thrusters (HEMPT) utilize the same high-voltage for ionization and acceleration.\textsuperscript{1,2} Despite these different concepts, these thrusters can all be characterized by analysing their plasma plume, i.e. the expelled ion beam. The thrust $T$ generated by the ion beam can be computed with

$$T = \sqrt{\frac{2\alpha\gamma^2\eta_e\eta_m\dot{m}_pP_{in}}{\eta_e\eta_m}},$$

where $\gamma = \cos(\theta)$ is the divergence efficiency, $\eta_e$ is the electrical efficiency and $\eta_m$ is the mass utilization efficiency, $\alpha$ is a correction factor for multiple ionization, $\dot{m}_p$ is the propellant massflow and $P_{in}$ is the electrical input power applied to the thruster.\textsuperscript{3}

Assessing the divergence efficiency can be done by performing a spatially resolved ion beam current measurement. This can be performed, e.g. by utilizing Langmuir probes or Faraday Cups.\textsuperscript{4}

The mass utilization efficiency is defined as $\eta_m = \dot{m}_i/\dot{m}_p$ where $\dot{m}_i$ is the ionized massflow of injected propellant. If the ratio of multiple charged ions is known, the mass utilization efficiency can be calculated with the ion beam current.\textsuperscript{3}

Evaluation of the ion charge ratio can be done with ExB probes or with spectroscopic analysis of the ion beam.\textsuperscript{5-7}

Since energy is lost to ionization, the electrical efficiency has to be differentiated into discharge efficiency $\eta_d$ and acceleration efficiency $\eta_v$ with $\eta_e = \eta_d\eta_v$. The acceleration efficiency is defined as ratio between actual ion energy $E_{ion}$ and maximum possible ion energy $E_{max}$. This ratio can, in case of an electrostatic thruster, be written as $\eta_v = V_{ion}/V_{acc}$, where $V_{ion}$ is the ion beam voltage and $V_{acc}$ is the applied acceleration voltage. The ion beam energy can be assessed by performing a retarding potential analysis.

The gridless Retarding Potential Analyser presented here can be operated as Faraday Cup as well as retarding potential analyser. Hence, a brief description of the operation principles of these measurement systems is given in the following.

A. Faraday Cup

A Faraday probe consists primarily of a conductive surface, which is immersed in the investigated plasma region. To circumvent the problem of secondary electron emission (SEM), the Faraday probe can be designed as a cup from conductive material with a separated negatively biased aperture in front of the cup as depicted in Fig. 1. Given that the electrical field of the aperture is strong enough to repel electrons of the beam as well as electrons from SEM, only the ion current is measured. Furthermore, this field attracts the ions, which is not of concern for fast ions of the beam, since the electrical field is comparatively weak. Slow charge-exchange ions on the other hand are susceptible for the weak electric field and therefore, can be removed from the ion beam.

Fig. 1 illustrates the ion and electron trajectories at the Faraday Cup. The line labelled with 1 depict the trajectory of a fast ion, which then lead to secondary electron emission (label 4) at impact of the cup. Line 2 depicts the path of an electron moving along with the ion beam. The electron is repelled from the electric field of the negatively biased aperture and therefore does not falsifying the measurement. Furthermore, a slow charge-exchange ion is illustrated (label 3), which is directed to the aperture.

A drawback of the Faraday Cup is the fact that only the ion beam current can be assessed, whereas the ion energy distribution can not be evaluated with the system.

Figure 1: Electron and ion trajectories of a Faraday cup.
B. Retarding Potential Analyser

Assessing the ion energy distribution of an ion beam, i.e. determining the acceleration efficiency of an electric propulsion thruster, can be performed via a retarding potential analyser (RPA). A RPA typically consists of a collector surface with differently biased grids in front. Fig. 2 depicts a typical gridded RPA system. The yellow grid is negatively biased to repel electrons travelling with ion beam, because they would lead to charge neutralization on the collector surface and hence, reducing the gaugeable ion current. Ion energy selection is performed by the red grid, which is biased to a varying positive voltage \( U_{i,sel} \). Only ions (charge \( q \)) with a higher kinetic energy than \( q \cdot U_{i,sel} \) can pass the grid and therefore, can be measured by the collecting surface (orange). Varying the ion repelling voltage while measuring the ion beam current at the collector allows to determine the ion energy distribution in the plasma beam. Because secondary electron emission at the collector surface would also lead to a falsified measurement, another negatively biased grid (blue) is part of the assembly to suppress SEM. A drawback of this assembly is the limited transmissivity of the grid system, which can only be calculated and is prone to errors since it depends on barely known plasma parameters. Additionally, these dependences lead to problems if significantly varying plasmas shall be evaluated with one design.

II. Gridless Retarding Potential Analyser – Concept

Since Faraday Cup and Retarding Potential Analyser are important measurement systems for electric propulsion system, Airbus Friedrichshafen developed a combined sensor to overcome the mentioned drawbacks and furthermore, to be able to evaluate ion beam current and the ion energy distribution with the same field disturbances caused by the probe.

Starting with a Faraday Cup, which is capable of precisely measuring the ion beam current, a modification to evaluate the ion energy was necessary without adding the gridded system of a RPA. Hence, the energy based ion selection has to be enabled in a different way. This requirement can be fulfilled if the collector cup itself is biased to a positive voltage.

The repelling force and especially the trajectory depends on the geometry of the biased cup. Evaluating the concept to find a suitable geometry has been done with the particle tracing software SIMION. Fig. 3 illustrates the results for one geometry. An electron beam (blue) as well as an ion beam (red) enter the active cup that is biased to the ion potential. All electrons get repelled from the electrical field created by the electron repeller aperture (1) in front of the cup. The ions are entering the cup and get repelled inside, since the electrical field of the cup (3) forms a spherical mirror for the ions. Additionally, a spacer is added between the positively biased cup and the negatively biased aperture.

In addition to the new concept for a gridless retarding potential analyser, the measurement electronics have
been developed to be integrated directly in the sensor. The electronics consist of a low noise transimpedance amplifier stage, a microcontroller for data acquisition and communication as well as auxiliary circuits to provide the required power and isolation.

The transimpedance amplifier stage allows a set of four different gain levels, allowing the measurement of ion beam current densities between 7.3 nA/cm\(^2\) up to 2.5 mA/cm\(^2\). The gain can be changed with the microcontroller during measurements, enabling the characterization of different operation points without exchanging the probe. Table 1 lists the possible sensitivity ranges and resolutions of the electronics.

Table 1: Sensitivity range and resolution of the gRPA electronic for the different gain settings.

<table>
<thead>
<tr>
<th>Gain</th>
<th>Sensitivity range</th>
<th>Resolution</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>2.5 mA/cm(^2)</td>
<td>610 nA/cm(^2)</td>
</tr>
<tr>
<td>2</td>
<td>250 (\mu)A/cm(^2)</td>
<td>61 (\mu)A/cm(^2)</td>
</tr>
<tr>
<td>3</td>
<td>25 (\mu)A/cm(^2)</td>
<td>12.2 (\mu)A/cm(^2)</td>
</tr>
<tr>
<td>4</td>
<td>15 (\mu)A/cm(^2)</td>
<td>7.3 (\mu)A/cm(^2)</td>
</tr>
</tbody>
</table>

A built-in 12 bit analog-to-digital-converter (ADC) of the microcontroller performs the digitalization of the transimpedance amplifier output. Hence, the measurement resolution is 1/4096 of the sensitivity range for ideal conditions. Especially in the higher gain settings, noise reduces the real measurement resolution as shown in table 1.

The communication between the single gRPA and the host measurement computer has been realized via RS-485, allowing a noise resistant, differential signal transmission. Furthermore, RS-485 is commonly used as serial bus, i.e. multiple gRPA require only one transmission cable that is looped through all of them. Hence, the wiring for even a large array of multiple gRPA is simple and can be brought into a vacuum chamber using e.g. a single KF-40 feedthrough.

III. Test results of the gridless retarding potential analyser

The calibration of the gRPA is performed by applying a current to the sensor. This has been performed with a Keithley 2400 Sourcemeter, which has a measurement accuracy of 300 pA. Fig. 4 illustrates the calibration for gain 1.

![Figure 4: Calibration results of the gridless retarding potential analyser with gain 1.](image-url)
The sensor shows a linear response to the applied calibration current as depicted in Fig. 4a. Furthermore, Fig. 4b depicts the measurement error of the electronics compared to an ideal response of the circuit. The error is less than 0.4% compared to an ideal response at low input signal and reduces further to less than 0.05% if the signal is above 25% of the sensitivity range. Running the sensor with the highest gain leads to the biggest errors due to a high transimpedance feedback resistance. Nevertheless, the error of the electronics is below ±2% at gain 4.

The gridless retarding potential analyser has already been tested extensively with a High Efficiency Multistage Plasma Thruster (HEMPT) at the Laboratory for Enabling Technologies, which is part of Airbus Friedrichshafen. An example of a typical measurement is depicted in Fig. 5.

Figure 5: Measurement results of the gridless retarding potential analyser with the mN-HEMPT of Airbus Friedrichshafen.

Figure 5a depicts a Faraday Cup measurement carried out with the gridless retarding potential analyser. The red crosses are data points, whereas the blue curve is the extrapolated ion beam shape. Since the jig-arm is blocked at 28° by the door of the vacuum chamber, the extrapolation has become necessary. There are two different peak signal intensities of the ion beam current, which can be explained with the asymmetric positioning of the thruster inside the vacuum chamber.

Figure 5b illustrates the ion energy distribution at an angle of 20° in the ion beam. Since the HEMPT has been operated at an anode voltage of 700 V, the maximum ion energy should be close to 700 eV, which is in accordance with the measurement data.

Besides the test with the mN-HEMPT at Airbus Friedrichshafen, a test has been performed with a Radiofrequency Ion Thruster (RIT) at the DLR Goettingen. The measured energy distribution is depicted in Fig. 6. An ion energy separation of 3 eV can be resolved.

Figure 6: Ion energy distribution of a RIT operating with an acceleration grid voltage of 1500 V.
Fig. 6. The RIT was operated at an acceleration grid voltage of 1500 V. The energy distribution illustrates that the gridless retarding potential analyser is capable of resolving at least 3 eV. Hence, the system can be used for precise ion energy distribution measurements and is matchable for gridded RPAs.

IV. The gRPA system for the AsteriX facility

Besides successful tests of the gRPA in the thruster test facility at Airbus Friedrichshafen, a plasma diagnostic system consisting of 13 gRPA is currently being implemented in the Acceptance test facility for electric Xenon thruster (AsteriX) at ArianeGroup in Lampoldshausen. The facility consists of a vacuum chamber of 3 m diameter, a length of 6 m and supports a pumping speed of 140,000 l/s in the current configuration, which can be upgraded to 350,000 l/s.11

An illustration of the gRPA array is depicted in Fig. 7. The vertical spacing of the sensors is 4°. The horizontal positioning is achieved with a vacuum compatible stepper motor, allowing a resolution of 0.1°. Since currently no retarding potential measurement is required, the gRPAs are operated as Faraday Cups. Nevertheless, they can easily be upgraded by exchanging the sensor potential cable, adding a high voltage power supply and adapting the software to the needs of a retarding potential analysis.

V. Conclusion

The gridless retarding potential analyser features ion energy and ion current measurements with the same device, i.e. causing the same disturbances to the plasma beam. Furthermore, due to the sophisticated design, no grids which limit the transmissivity are needed for ion energy selection. The developed electronics is capable of ion current measurements in the range of 7.2 nA/cm² up to 2.5 mA/cm². In order to maintain a reasonable resolution the gain of the internal transimpedance amplifier can be controlled in 4 steps via commanding the implemented microcontroller. The communication is performed with a RS-485 connection. Operation as retarding potential analyser is in the current development stage possible up to 1500 V.

References